Light Quark Dependence of the Isgur-Wise Function from QCD Sum rules[1]

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Abstract

We study light quark dependence of the Isgur-Wise function for $B_a \to D_a$ and $B_a \to D_a^*$ in the framework of QCD sum rules. At zero recoil , all the Isgur-Wise functions equal as required by heavy quark symmetry and at non-zero recoil, the Isgur-Wise function for B_s decay falls faster than that for $B_{u,d}$ decay , which is just contrary to the recent prediction of the heavy meson chiral perturbation theory. As by-products, we also estimate SU(3) breaking effects in the mass and the decay constant.

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I   Introduction

Recently, there has been a great deal of interest in weak decays of heavy mesons made from one heavy quark and one light quark. As heavy quark goes into infinite mass limit, all form factors for $B \to D$ and $B \to D^*$ can be expressed in terms of a single universal function [1], the so-called Isgur-Wise function [2]. It is the property of the Isgur-Wise function–the normalization at the zero-recoil point [1,2,3] that leads to the model independently extraction of the Kabayashi-Makawa matrix element V_{cb}. The knowledge of the Isgur-Wise function will be required for any phenomenological applications of heavy quark symmetry to exclusive weak decays of heavy mesons. Therefore, it is very interesting and necessary to investigate the Isgur-Wise function and its properties.

The Isgur-Wise function represents the nonperturbative dynamics of weak decays of heavy mesons. It depends not only on the dimensionless product $v \cdot v'$ of the initial and final mesonic velocities, but also on the light quark flavor of the initial and final mesons [4,5]. In the past few years, many different nonperturbative methods were developed to investigate the velocity product $v \cdot v'$ dependence of the Isgur-Wise function [6-13]. But for light quark flavor dependence of the Isgur-Wise function, Only chiral perturbation theory of the heavy mesons [14] was developed to study it [5], no investigation from other methods can be found in the literatures . However, QCD sum rule approach [15] involving nonperturbative effects is based on the QCD theory of strong interaction, it has many advantages over others: it is not only suitable for investigations of $v \cdot v'$ dependences of the Isgur- Wise function but also suitable for investigating its light quark flavor dependence. In [10-13], QCD sum-rule was used to calculate the $v \cdot v'$ dependence of the Isgur-Wise function. In this paper, we will use QCD sum rules to calculate its light quark flavor dependence.

This paper is organized as follows: section II presents the sum rule for the decay constant. The sum rule for the Isgur-Wise function is derived in section III. Section IV gives the numerical analysis and the final section is reserved for Summary and discussion.

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II. Sum rule for the decay constant

In order to investigate light quark flavor dependence of the Isgur-Wise function , one should know the light quark flavor dependence of the decay constant of the heavy meson. i.e., to derive the sum rule for decay constant including the light quark dependence in the heavy quark effective theory (HQET).

In HQET, the low energy parameter $F_a(\mu)$ of heavy meson $M_a(\bar{q}Q)$ is defined by [10,16]

$$< 0|\bar{q}\Gamma h_Q|M_a(v) > = \frac{F_a(\mu)}{2}Tr[\Gamma M(v)], \tag{1}$$

where $M(v)$ is the spin wavefunction of heavy meson $M_a(v)$ in HQET

$$M(v) = \sqrt{m_Q}\frac{1+ \not{v}}{2}(-i\gamma_5). \tag{2}$$

In leading order ,the decay constant $f_{M_a} \simeq F_a(\mu)/\sqrt{m_{M_a}}$. It should be emphasized that here and after, the subscript $a = u, d, s$ specifies the light antiquark flavor $\bar{q} = \bar{u}, \bar{d}, \bar{s}$ of the heavy meson $M_a(\bar{q}Q)$.

The standard procedure to calculate the physical quantity with QCD sum rule can be found in [15]. In this paper, we follow the method in [10] given by Neubert. To derive the sum rule for the decay constant , one can consider the two-point correlation function in HQET,

$$\pi_5(\omega) = i \int d^4x e^{ik\cdot x} < 0|TA_5^{(v)}(x), A_5^{(v)+}(0)|0 >, \tag{3}$$

where $A_5^{(v)} = \bar{q}\gamma_5 h_Q$ is the effective peseudoscalar current and $\omega = 2k \cdot v$, k is the residual momentum .The starting point of QCD sum rule is to calculate the correlation function $\pi_5(\omega)$ in two different ways. First, in not so deep Euclidean region of ω, where nonperturbative effects enter but do not dominate, by the operator product expansion(OPE), one can expand $\pi_5(\omega)$ as

$$\pi_5(\omega) = \pi_5^P(\omega) + \pi_5^{NP}(\omega). \tag{4}$$

The first term $\pi_5^P(\omega)$ is just the usual perturbative contribution, which corresponds to the identity operator in the OPE , and is expressed through a dispersion relation

$$\pi_5^P(\omega) \;=\; \frac{1}{\pi}\int ds \frac{\rho_P(s)}{s-\omega} + subtractions. \tag{5}$$

The perturbative spectral density $\rho_p(s)$ can be computed as usual

$$\rho_P(\omega) \;=\; \frac{3}{8\pi}\sqrt{\omega^2-4m_q^2}(\omega+2m_q)\Theta(\omega-2m_q) \tag{6}$$

(m_q is the mass of the light quark q). The second term $\pi_5^{NP}(\omega)$ is the nonperturbative contributions, according to SVZ [15], which are parameterized by the quark condensate, the gluon condensate and the quark-gluon mixed condensate etc, and we obtain

$$
\begin{aligned}
\pi_5^{NP}(\omega) \;=\;\; & <0|\bar{q}q|0>[\frac{1}{\omega}+\frac{m_q}{2\omega^2}+\frac{m_q^2}{\omega^3}]\\
& + <0|\frac{\alpha_s}{\pi}GG|0>\frac{m_q}{2\omega^3}[1-ln\frac{\omega}{\mu}]\\
& -\frac{g_s}{2\omega^3}<0|\bar{q}\sigma Gq|0>\\
& +\frac{8\pi\alpha_s}{27\omega^4}<0|\bar{q}q|0>^2 .
\end{aligned}
\tag{7}
$$

On the other hand, the correlation function can also be reexpressed in terms of hadronic resonance states and continuum states by a dispersion relation as

$$\pi_5^{Ph}(\omega) \;=\; \frac{1}{\pi}\int_{\omega_a^c}^{\infty}ds\frac{\rho_H(s)}{s-\omega-i\epsilon}+\frac{|<0|\bar{q}\gamma_5 h_Q(v)|M(v)>|^2}{(2\bar{\Lambda}_a-\omega-i\epsilon)m_Q}+subtractions, \tag{8}$$

where $\bar{\Lambda}_a = M_a - m_Q$ is the parameter of HQET [17] and ω_a^c is the threshold of the continuum states. Assuming the quark-hadron duality, the continuum spectral function ρ_H can be approximated by the perturbative spectral function ρ_p. Therefore one gets the sum rule

$$\pi_5^{Th}(\omega) \;=\; \pi_5^{Ph}(\omega)+subtractions. \tag{9}$$

In order to enhance contribution of the lowest lying resonance state and improve the convergence of the OPE , the Borel transformation defined as

$$\frac{1}{T}\hat{B}_T^{(\omega)} \;=\; \lim_{\substack{-\omega,\ n\to\infty \\ T=-\omega/n\ fixed}} \frac{\omega^n}{\Gamma(n)}[-\frac{d}{d\omega}]^n \tag{10}$$

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must be applied . So the final sum rule reads

$$
\begin{aligned}
F_a^2(\mu)e^{-2\bar{\Lambda}/T} &= \frac{3}{8\pi^2}\int_{2m_q}^{\omega_a^c}ds\sqrt{s^2-4m_q^2}[2m_q+s]e^{-s/T} \\
&\quad - <0|\bar{q}q|0>[1-\frac{m_q}{2T}+\frac{m_q^2}{2T^2}]-\frac{<0|\frac{\alpha_s}{\pi}GG|0>m_q}{4T^2}[\gamma-0.5-ln\frac{T}{\mu}] \\
&\quad +\frac{g_s<0|\bar{q}\sigma Gq|0>}{4T^2}+\frac{4\pi\alpha_s}{81T^3}<0|\bar{q}q|0>^2 & (11) \\
&= G(T^{-1}), & (12)
\end{aligned}
$$

with $\gamma = 0.5772$ being the Euler constant. Taking the derivative with respect to the inverse of T , one can obtain the sum rule for $\bar{\Lambda}_a$

$$
\bar{\Lambda}_a = -\frac{G'(T^{-1})}{2G(T^{-1})}. \tag{13}
$$

From these sum rules , one can observe that the light quark flavor dependence of $F_a(\mu)$ is represented by that of the condensates $<0|\bar{q}q|0>$, $<0|\bar{q}\sigma Gq|0>$ and m_q. In the next section , these sum rules will be used to obtain the sum rule for the Isgur-Wise function.

III.Sum rule for the Isgur-Wise function

The Isgur-Wise function $\xi_a(v\cdot v',\mu)$ is defined by the matrix element at the leading order in $\frac{1}{m_Q}$[10,18]

$$
< M_a(v')|\bar{h}_{Q_2}(v')\Gamma h_{Q_1}(v)|M_a(v) > = -\xi_a(v\cdot v',\mu)Tr[\bar{M}(v')\Gamma M(v)], \tag{14}
$$

which is valid for an arbitrary matrix Γ .

To derive the sum rule for the Isgur-Wise function , one should consider the three-point correlation function in HQET

$$
\tilde{\pi}(\omega,\omega',y) = \int d^4x d^4z e^{i(k'\cdot x-k\cdot z)} <0|T\{[\bar{q}\gamma_5 h_{Q_1}(v')]_x,[\bar{h}_{Q_1}(v')\Gamma h_{Q_2}(v)]_0,[\bar{h}_{Q_2}(v)\gamma_5 q]_z\} \tag{15}
$$

with $y = v\cdot v'$,$\omega = 2k\cdot v$ and$\omega' = 2k'\cdot v'$. The weak current in Eq.(15) is $\bar{h}_{Q_1}(v')\Gamma h_{Q_2}(v)$. To be convenient, let's factorize out the Lorentz structure by defining $\tilde{\pi}(\omega,\omega',y) = \pi(\omega,\omega',y)Tr[\frac{1+\psi'}{2}\Gamma\frac{1+\psi'}{2}]$. the perturbative spectral density ρ_{pert} for $\pi^P(\omega,\omega',y)$ is

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$$\rho_{pert}(\omega, \omega', y) = \frac{3}{16\pi} \frac{[\omega + \omega' + 2(1+y)m_q]}{(1+y)\sqrt{y^2-1}} \theta(\omega)\theta(\omega')\theta[2y\omega\omega' - \omega'^2 - \omega^2 - 4m_q^2(y^2-1)] \quad (16)$$

The next standard step is to write the correlation function by using dispersion relations in ω and ω'

$$\pi^{Ph}(\omega, \omega', y) = \frac{\xi_a(y,\mu)F_a^2(\mu)}{(2\Lambda_a - \omega - i\epsilon)(2\Lambda_a - \omega_\prime - i\epsilon)} + \frac{1}{\pi}\int_{\omega^c}^{\infty} ds \int_{\omega^c}^{\infty} ds' \frac{\rho_H(s,s',y)}{(s-\omega-i\epsilon)(s'-\omega'-i\epsilon)}$$

$$+subtractions \quad (17)$$

with $\rho_H(s, s', y) = \rho_{pert}(s, s', y)$ by assuming the quark-hadron duality.

After applying Borel transformations with respect to ω as well as ω' to improve the matching between $\pi^{Ph}(\omega, \omega', y)$ and $\pi^{Th}(\omega, \omega', y)$

$$\hat{B}_{\tau'}^{(\omega)}\hat{B}_{\tau}^{(\omega)}\pi^{Ph}(\omega, \omega', y) = \hat{B}_{\tau'}^{(\omega)}\hat{B}_{\tau}^{(\omega)}\pi^{Th}(\omega, \omega', y), \quad (18)$$

we obtain the sum rule

$$\xi_a(y,\mu)F_a^2(\mu)e^{-2\bar{\Lambda}_a/T} = \frac{1}{\pi}\int_0^{\omega^c} ds \int_0^{\omega^c} ds' \rho_{Pert}(s, s', y)e^{-(s+s')/2T} + \pi_B^{NP}(y, T), \quad (19)$$

where we have set $\tau' = \tau = 2T$ as observed in [19]. The borelized nonperturbative contribution $\pi_B^{NP}(y, T)$ is

$$\begin{aligned}
\pi_B^{NP}(y, T) &= \hat{B}_{\tau'}^{(\omega)}\hat{B}_{\tau}^{(\omega)}\pi^{NP}(\omega, \omega', y)|_{\tau'=\tau=2T} \\
&= -<0|\bar{q}q|0>[1 - \frac{m_q}{2T} + \frac{m_q^2}{4T^2}(1+y)] \\
&\quad + <0|\frac{\alpha_s}{\pi}GG|0>[\frac{y-1}{48T(1+y)} - \frac{m_q}{4T^2}(\gamma - 0.5 - \ln\frac{T}{\mu})] \\
&\quad + \frac{g_s <0|\bar{q}\sigma Gq|0>}{4T^2}\frac{2y+1}{3} + \frac{4\pi\alpha_s <0|\bar{q}q|0>^2}{81T^3}y. \quad (20)
\end{aligned}$$

Since the integration domain is symmetric in s and s', changing variables $\alpha = \frac{s+s'}{2}$, $\beta = s - s'$ and improving the continuum threshold model as suggested in [10] by Neubert, we get the sum rule for the Isgur-Wise function:

$$\xi_a(y,\mu) = \frac{K(T, \omega_a^c, y)}{K(T, \omega_a^c, 1)}, \quad (21)$$

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where

$$K(T, \omega_a^c, y) = \quad \frac{3}{8\pi^2}(\frac{2}{1+y})^2 \int_{m_q\sqrt{2(1+y)}}^{\omega^c} d\alpha[\alpha + (1+y)m_q]\sqrt{\alpha^2 - 2(1+y)m_q^2}e^{-\alpha/T}$$

$$- <0|\bar{q}q|0> [1 - \frac{m_q}{2T} + \frac{m_q^2}{4T^2}(1+y)]$$

$$+ <0|\frac{\alpha_s}{\pi}GG|0> [\frac{y-1}{48T(1+y)} - \frac{m_q}{4T^2}(\gamma - 0.5 - \ln\frac{T}{\mu})]$$

$$+ \frac{g_s<0|\bar{q}\sigma Gq|0>}{4T^2}\frac{2y+1}{3} + \frac{4\pi\alpha_s<0|\bar{q}q|0>^2}{81T^3}y. \tag{22}$$

In the above derivation, we have used the sum rule for $F_a(\mu)$.

IV.Numerical analysis

In the numerical analysis of sum rules, we take the following values for parameters such as condensates and m_q[20-24]

$$<0|\bar{u}u|0> = <0|\bar{d}d|0> = (-0.23GeV)^3$$

$$<0|\bar{u}\sigma Gu|0> = <0|\bar{d}\sigma Gd|0> = 0.8GeV^2 <0|\bar{u}u|0>$$

$$\frac{<0|\bar{s}s|0>}{<0|\bar{u}u|0>} = \frac{<0|\bar{s}\sigma Gs|0>}{<0|\bar{u}\sigma Gu|0>} = 0.8 \quad ; \quad <0|\frac{\alpha_s}{\pi}GG|0> = 0.012GeV^4$$

$$m_u \approx m_d \approx 0 \quad ; \quad m_s \simeq 0.15GeV \tag{23}$$

and set the scale $\mu = 1GeV$, which equals about two times of $\bar{\Lambda}_{u,d,s}$ (see below). For the continuum model $\omega^c = \sigma(y)\omega_a^c$, we use the experiment preferred model $\sigma(y) = \frac{y+1}{2y}$ as suggested in [10] by Neubert.

As $a = u, d$, all sum rules for $\bar{\Lambda}_a$, F_a and ξ_a have been evaluated in [10,16,18]. In the following, we will evaluate these sum rules as $a = s$ and calculate the ratios $R_F = F_s/F_{u,d}$ and $R_{IW} = \xi_s/\xi_{u,d}$.

In Fig.1, we show $\bar{\Lambda}_s$ and F_s as a function of T for different ω_s^c. Within $\omega_s^c = 1.8 \sim 2.4GeV$ and $T = 0.6 \sim 1.0GeV$, where QCD sum rules calculation is reliable, we have

$$\bar{\Lambda}_s \simeq 0.62 \pm 0.07GeV \quad , \quad F_s \simeq 0.36 \pm 0.05GeV^{3/2}. \tag{24}$$

For completeness, we list the values for $\bar{\Lambda}_{u,d}$ and $F_{u,d}$:

$$\bar{\Lambda}_{u,d} \simeq 0.55 \pm 0.07 GeV \quad , \quad F_{u,d} \simeq 0.32 \pm 0.05 GeV^{3/2}. \tag{25}$$

Therefore, with the above values $\bar{\Lambda}_a$ and F_a, one can calculate the $SU(3)$ breaking effects in the mass of the heavy meson $M(\bar{q}_a Q)$ to the leading order in $1/m_Q$

$$\Delta M = m_{M_s} - m_{M_{u,d}} = \bar{\Lambda}_s - \bar{\Lambda}_{u,d} \tag{26}$$

and the ratio $R_F = F_s/F_{u,d}$. However, in order to reduce the errors, writing the mass difference $\Delta M = \bar{\Lambda}_s - \bar{\Lambda}_{u,d}$ and the ratio $R_F = F_s/F_{u,d}$ with the corresponding sum rules, in Fig.2, one can find that ΔM and R_F depend on T very weakly within $\omega_{u,d}^c = 1.7 \sim 2.3 GeV$ and $\omega_s^c = 1.8 \sim 2.4 GeV$. From Fig.2(a) follows

$$\Delta M = 69 \pm 5 MeV, \tag{27}$$

which is in good agreement with the recent experiment results [25,26]

$$m_{B_s} - m_B = 90 \pm 6 MeV, m_{D_s} - m_D = 99.5 \pm 0.6 MeV. \tag{28}$$

From Fig.2(b), we get the ratio

$$R_F = 1.13 \pm 0.01. \tag{29}$$

In Fig.3, the Isgur-Wise function ξ_s is shown as a function of y. Changing ω_s^c in $1.8 \sim 2.4 GeV$ and T in $0.7 \sim 0.9 GeV$, the Isgur-Wise function varys in the band region. Obviously, the dependence on these parameters is very weak. At the center of the sum rule window T=0.8GeV, we obtain the slope parameter ϱ_a^2 defined as $\varrho_a^2 = -\xi_a'(y = 1, \mu)$

$$\varrho_s^2 = 1.09 \pm 0.04, \tag{30}$$

the uncertainty is due to the variation of ω_s^c. One can compare with

$$\varrho_{u,d}^2 = 1.01 \pm 0.02. \tag{31}$$

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and find that SU(3) breaking effects in the slope parameter is not large but the important thing is

$$\varrho_s^2 > \varrho_{u,d}^2. \tag{32}$$

This result just indicates that the Isgur-Wise function ξ_s falls faster than the Isgur-Wise function $\xi_{u,d}$ as shown below. Obviously, all these slope parameters satisfy the Bjorken sum rule $\varrho_a^2 > 0.25$ [27] but violate the Voloshin sum rule $\varrho_a^2 < 0.75^3$[28].

In Fig.4, we show $R_{IW} = \xi_s/\xi_{u,d}$ as a function of y at $T = 0.8 GeV$ for different $\omega_{u,d}^c = 1.7 \sim 2.3 GeV$ and $\omega_s^c = \omega_{u,d}^c + 0.1 GeV$. One can find that the ratio R_{IW} displays a soft dependence on $\omega_{u,d,s}^c$.

In order to show how R_{IW} depends on T, in Fig.5, we plots R_{IW} as a function of T at $y = 1.6$, which approximately corresponds to the largest recoil point $q^2 = 0$ for $B_{u,d} \rightarrow D_{u,d} + l\nu$. In the stable region, we get

$$R_{IW} \simeq (95 \pm 2)\%, \tag{33}$$

where the uncertainty is ascribed to the uncertainty in $\omega_{u,d,s}^c$ and T.

It should be pointed out that in the evaluations of sum rules for ξ_a and R_{IW}, the continuum model is chosen as $\sigma(y) = \frac{y+1}{2y}$. This may cause large errors in ξ_a and R_{IW}. As discussed in [10], one knows

$$\frac{y + 1 - \sqrt{y^2 - 1}}{2} \leq \sigma(y) \leq 1, \tag{34}$$

and the model $\sigma_{max} = 1$ and $\sigma_{min} = \frac{y+1-\sqrt{y^2-1}}{2}$ respectively constituents the upper bound and the lower bound for ξ_a . For R_{IW}, as shown in Fig.6, the model σ_{max} and σ_{min} just gives the lower bound and the upper bound respectively. Although different continuum model gives different value for R_{IW}, one can find that all of these values clearly give

$$R_{IW} < 1 \quad , \quad for\ y \neq 1. \tag{35}$$

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[3]However, it should be emphassed that this violation of the Voloshin sum rule depends on the choice of $\sigma(y)$. If choosing $\sigma(y) = 1$ as discussed in [12], one finds ϱ_a^2 can satisfy the Voloshin sum rule.

Therefore we conclude that $R_{IW} < 1$(for $y \neq 1$) is independent of the model choice $\sigma(y)$.

V. Summary and Discussion.

In summary , we have determined the parameters $\bar{\Lambda}_s$ and F_s, and given the Isgur-Wise function $\xi_s(y, \mu)$. Also we have shown how large SU(3) breaking effects exist in the mass,the decay constant and the Isgur-Wise function. It is very interesting to find that the Isgur-Wise function for $B_s \rightarrow D_s$ falls faster than the Isgur-Wise function for $B_{u,d} \rightarrow D_{u,d}$, which is just contrary to the prediction of the heavy meson chiral perturbation theory where only SU(3) breaking chiral loops are calculated [5]. Our result $R_{IW} \leq 1$ agrees with that of the BSW model [6]. It is expected that the future experiments can test this result and reveal the underlying mechanism of SU(3) breaking effects.

Acknowledgment

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Figure Captions

Fig.1: $\bar{\Lambda}_s$ and F_s as a function of T for different ω_s^c: Dashed line: $\omega_s^c = 1.8GeV$, Solid line: $\omega_s^c = 2.1GeV$, Dotted line: $\omega_s^c = 2.4GeV$.

Fig.2: The mass difference $\Delta M = \bar{\Lambda}_s - \bar{\Lambda}_{u,d}$ and the ratio $R_F = F_s/F_{u,d}$ as a function of T ($\omega_s^c = \omega_{u,d}^c + 0.1GeV$): Dashed line: $\omega_{u,d}^c = 1.7GeV$, Solid line: $\omega_{u,d}^c = 2.0GeV$, Dotted line: $\omega_{u,d}^c = 2.3GeV$.

Fig.3: The Isgur-Wise function ξ_s as a function of y . The band corresponds to variations of ω_s^c in $1.8GeV \sim 2.4GeV$ and T in $0.7GeV \sim 0.9GeV$.

Fig.4: The ratio $R_{IW} = \xi_s/\xi_{u,d}$ as a function of y at T=0.8GeV ($\omega_s^c = \omega_{u,d}^c + 0.1GeV$): Dashed line: $\omega_{u,d}^c = 1.7GeV$, Solid line: $\omega_{u,d}^c = 2.0GeV$, Dotted line: $\omega_{u,d}^c = 2.3GeV$.

Fig.5: The ratio R_{IW} as a function of T at y=1.6($\omega_s^c = \omega_{u,d}^c + 0.1GeV$): Dashed line: $\omega_{u,d}^c = 1.7GeV$, Solid line: $\omega_{u,d}^c = 2.0GeV$, Dotted line: $\omega_{u,d}^c = 2.3GeV$.

Fig.6: The ratio $R_{IW} = \xi_s/\xi_{u,d}$ as a function of y at T=0.8GeV for different models σ_{max} (Fig.6(a)) and σ_{min} (Fig.6(b)). ($\omega_s^c = \omega_{u,d}^c + 0.1GeV$): Dashed line: $\omega_{u,d}^c = 1.7GeV$, Solid line: $\omega_{u,d}^c = 2.0GeV$, Dotted line: $\omega_{u,d}^c = 2.3GeV$.

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